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ABSTRACT

PLASQUI, G., and K. R. WESTERTERP. Accelerometry and Heart Rate as a Measure of Physical Fitness: Cross-Validation. *Med. Sci. Sports Exerc.*, Vol. 38, No. 8, pp. 1510–1514, 2006. **Purpose:** We recently reported on a new method to assess physical fitness, based on the combined use of accelerometry and heart rate (HR) registration. This study tested the validity of the prediction formula in a group of healthy young adults. **Methods:** Twenty-six healthy subjects performed a maximal incremental test on a bicycle ergometer to determine $\dot{V}O_{2max}$. A triaxial accelerometer and a HR monitor were worn for 7 d under free-living conditions. The prediction formula developed in a previous experimental group (EXP) was applied on the cross-validation group (CV). **Results:** No difference was found in subjects' characteristics between the EXP and CV groups except for accelerometer output (activity counts). Although measured $\dot{V}O_{2max}$ could be predicted for 80% ($P < 0.0001$), a paired *t*-test showed a significant difference between measured and predicted $\dot{V}O_{2max}$ (178 mL·min^{-1}; $P = 0.015$). Because of the difference in activity between the EXP and the CV groups, all data were combined and sorted according to activity counts, then two new groups were formed. As a result, EXP and CV groups were created that did not significantly differ in activity or any other parameters. The formula developed in the new experimental group ($R^2 = 0.74$; $P < 0.0001$) explained 72% ($P < 0.0001$) of the variation in $\dot{V}O_{2max}$ in the cross-validation group, a paired *t*-test showed no difference between measured and predicted $\dot{V}O_{2max}$, and Bland–Altman plotting showed no systematic bias. **Conclusion:** Although a good correlation was seen between measured and predicted $\dot{V}O_{2max}$ in the cross-validation group, care should be taken in applying the prediction formula on groups that differ in physical activity from the current study population. **Key Words:** MAXIMAL OXYGEN UPTAKE, TRIAXIAL ACCELEROMETER, BODY COMPOSITION, SUBMAXIMAL EXERTION, DAILY LIFE

Maximal oxygen uptake ($\dot{V}O_{2max}$), the most widely used measure of physical fitness, is inversely related with several health outcomes, such as cardiovascular disease and coronary artery disease (25). $\dot{V}O_{2max}$ can be accurately measured in a laboratory setting using standardized protocols that require sophisticated equipment and maximal exertion of the subject. The physiological importance of $\dot{V}O_{2max}$ as a measure of aerobic fitness, as an indication of physical activity, and as a health parameter has led to the development of various maximal and submaximal field tests to estimate $\dot{V}O_{2max}$ (1,4,8,11,14,18,21). Although useful for research purposes, these tests are limited in their applicability for personal assessment by exertion level and the requirements for specific procedures.

Weyand et al. (24) developed a fitness index by the combined use of foot–ground contact times and heart rate (HR) monitoring during running on a treadmill. The fitness index correlated well (r = 0.90) with $\dot{V}O_{2max}$, and the predictive power was independent of running speed. Although this fitness index is a promising tool to assess physical fitness, its usefulness is limited to a laboratory test on a treadmill, and it has not been tested in the field at volitional running or (more desirably) walking speeds.

Most submaximal protocols are based on the inverse relationship between HR at a given exercise intensity and physical fitness; that is, when the intensity of a certain activity is known and HR is registered, $\dot{V}O_{2max}$ can be predicted. Developing a fitness index for application in daily life requires a tool that will estimate the intensity of different activities.

We recently reported on a new fitness index that was based on the combined use of accelerometry and HR registration and that could be used in daily life without requiring a specific protocol (22). When the output of the accelerometer (activity counts per minute) was used to define the intensity of the activity performed (23) (i.e., the average intensity over the monitoring time was used), the corresponding HR would be inversely related with physical fitness. Multiple regression analysis showed that this fitness index, defined as HR over activity counts per minute (HR·ACM^{-1}), contributed significantly (additional explained variation from fitness index beyond that of age, gender, and body mass (BM) was 9%, partial R = −0.48, $P = 0.02$) to the explained variation in $\dot{V}O_{2max}$. The present study was designed to validate the prediction equation in a group of healthy subjects with varying degrees of physical fitness.

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Submitted for publication February 2005.
Accepted for publication March 2006.

0195-9131/06/3808-1510/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/01.mss.0000228942.55152.84

SUBJECTS AND METHODS

Subjects. Subjects were 26 healthy adults between the ages of 18 and 50 yr, most of them recruited from the university. Information about the protocol of the study was provided, informed written consent was obtained, and the study was approved by the ethics committee of Maastricht University. This group will be referred to as the cross-validation (CV_1) group. The experimental (EXP_1) group used to develop the prediction formula has been described in a previous study (22). Physical characteristics of the CV_1 group and the EXP_1 group are presented in Table 1.

Maximal aerobic power. $\dot{V}O_{2max}$ was determined during an incremental test on a cycle ergometer according to the protocol of Kuipers et al. (12). After a warm-up of 5 min at 100 W for men and 75 W for women, workload was increased by 50 W every 2.5 min. When HR reached a value of 35 bpm below the age-predicted maximal HR (220 bpm − age) or the respiratory quotient (RQ) exceeded 1, workload was increased by 25 W every 2.5 min until exhaustion. Subjects were equipped with a mouthpiece and nose clip, and expired air was continuously analyzed for O_2 consumption and CO_2 production (Oxycon-β, Bunnik, The Netherlands). During the latter stages of the test, each subject was verbally encouraged by the test operators to give a maximal effort. Achievement of $\dot{V}O_{2max}$ was accepted if two of three of the following conditions were met: subject's respiratory exchange ratio (RER) was > 1.1, maximal HR was > 85% of age-predicted maximal HR (220 − age), or the $\dot{V}O_2$ curve showed a leveling off. Because most of the subjects were already familiar with the protocol, these criteria were met by all subjects.

Anthropometrics. Body mass was determined to the nearest 0.1 kg (SECA, model 707, Hamburg, Germany) before the bicycle ergometer test, with subjects in light sports clothing and without shoes.

Accelerometry. The triaxial accelerometer for movement registration (Tracmor; Philips Research, Eindhoven, The Netherlands) was used to register daily life activity. The accelerometer was worn consecutively for 7 d during waking hours, except during water activities. The accelerometer is worn at the lower back by means of an elastic belt. It registers accelerations in the anteroposterior, mediolateral, and longitudinal axes of the trunk. Data were collected and stored minute by minute and downloaded to computer files, and the sum of all three axes was used as the activity measure. Tracmor output is defined as activity counts per minute (ACM).

Heart rate monitoring. Heart rate was continuously registered for seven consecutive days using a Polar (S610i) HR monitor (Polar Electro Oy, Kempele, Finland). Subjects were instructed on how to use the transmitter belt and the wristwatch and were asked to wear the monitor at the same time as the accelerometer (i.e., waking hours, except during water activities). The HR monitor was programmed to store heartbeat every minute, allowing synchronization in time with the accelerometer. After 7 d, the data were downloaded to computer files.

Fitness index. The accelerometer and HR monitor, both programmed to provide one data point each minute, were synchronized in time. The data of all 7 d were combined as one dataset. When the HR monitor generated inaccurate data (because of flawed contact of the transmitter belt with the skin or telemetric interference from other electric devices) the corresponding accelerometer value was also removed. On average, 740 $min \cdot d^{-1}$ were used to establish the fitness index. For each subject, one average value (over the entire 7-d registration) was calculated for both ACM and HR (bpm). The ratio of $HR \cdot ACM^{-1}$ was then used as our fitness index (22).

Comparison of EXP and CV group. Student's *t*-test for unpaired data was used to compare the EXP_1 with the CV_1 group. A significant difference for activity counts (P = 0.006) was found (the EXP_1 group was significantly more active than the CV_1 group) (Table 1). Therefore, subjects from both the EXP_1 and the CV_1 groups were combined (N = 51) and sorted for activity counts. Two new groups were formed by coding all odd numbers 0 and even numbers 1, creating a new EXP group and CV group that did not differ in physical activity. These groups will be referred to as EXP_2 and CV_2. Characteristics of the EXP_2 and CV_2 groups are presented in Table 2. Student's *t*-test for unpaired data showed no significant differences in any of the parameters between groups (Table 2).

Statistics. Both the EXP and CV groups were compared using Student's *t*-test for unpaired data. Multiple linear regression was used to develop the prediction formula in EXP_2. In the CV groups, Student's *t*-test for paired data was used to test differences between predicted (equations developed in EXP groups) and measured $\dot{V}O_{2max}$. Assuming that a mean difference ± SD of 300 ± 400 $mL \cdot min^{-1}$ (~10% of the average $\dot{V}O_{2max}$) would be a physiologically and methodologically significant

TABLE 1. Subject characteristics of experimental group 1 (EXP_1) (22) and cross-validation 1 (CV_1) group. Values are mean ± SD.

	EXP_1	CV_1
N (M/F)	25 (10/15)	26 (14/12)
Age (yr)	28 ± 7	29 ± 6
Body mass (kg)	68.3 ± 12.6	71.2 ± 12.0
Body mass index ($kg \cdot m^{-2}$)	23.1 ± 3.2	22.7 ± 2.7
Activity counts (counts per minute)	478 ± 117	394 ± 89*
$HR \cdot ACM^{-1}$ (beats per activity count)	0.19 ± 0.05	0.21 ± 0.05
$\dot{V}O_{2max}$ ($mL \cdot min^{-1}$)	2975 ± 696	3177 ± 752

* Significant difference between groups (P = 0.006). $HR \cdot ACM^{-1}$, heart rate over activity counts per minute.
Values are mean ± SD.

TABLE 2. Subject characteristics of experimental group 2 (EXP_2) and cross-validation group 2 (CV_2) after stratification for physical activity. Values are mean ± SD.

	EXP_2	CV_2
N (M/F)	26 (10/16)	25 (14/11)
Age (yr)	28 ± 6	30 ± 7
Body mass (kg)	69.6 ± 11.2	70.0 ± 13.5
Body mass index ($kg \cdot m^{-2}$)	22.7 ± 2.7	23.6 ± 4.2
Activity counts (counts per minute)	439 ± 125	432 ± 97
$HR \cdot ACM^{-1}$ (beats per activity count)	0.20 ± 0.06	0.20 ± 0.05
$\dot{V}O_{2max}$ ($mL \cdot min^{-1}$)	3054 ± 643	3103 ± 814

$HR \cdot ACM^{-1}$, heart rate over activity counts per minute.

difference with 25 subjects, we had a power of 0.95 to detect such a difference. Linear regression was used to test agreement between predicted and measured $\dot{V}O_{2max}$. Bland–Altman plotting (2) and linear regression were used to detect systematic differences between measured and predicted $\dot{V}O_{2max}$. All analyses were done with Statview 5.0 for Macintosh (SAS Institute Inc., NC) and SPSS 10.0 for Macintosh (SPSS Inc., Chicago, IL). The level for statistical significance was set at $P < 0.05$.

RESULTS

EXP_1 and CV_1. Predicted $\dot{V}O_{2max}$ (equation 1) correlated well with measured $\dot{V}O_{2max}$ (R = 0.90, $P < 0.0001$), and the standard error of estimate (SEE, square root of the average squared error of prediction) was 341 $mL \cdot min^{-1}$, or 10.7% of the average $\dot{V}O_{2max}$. Predicted $\dot{V}O_{2max}$ was 178 ± 349 (mean ± SD) $mL \cdot min^{-1}$, or 5.6% lower than measured ($P = 0.015$). Bland–Altman plotting and linear regression showed a significant positive relation ($P = 0.007$) between the average of predicted and measured $\dot{V}O_{2max}$ and the difference between both (Fig. 1).

$$\dot{V}O_{2max} = 2714 - 31.48*\text{age} + 592*\text{gender} + 25.46*\text{BM} - 4401*\text{HR}\cdot\text{ACM}^{-1} \quad [1]$$

where age is in years, gender = 0 for women and 1 for men, BM is body mass in kilograms, and $HR \cdot ACM^{-1}$ is the fitness index defined as HR over activity counts per minute.

EXP_2 and CV_2. The same independent variables as in equation 1 were used to predict $\dot{V}O_{2max}$ in the EXP_2 group. BM, age, gender, and $HR \cdot ACM^{-1}$ significantly contributed to the prediction of $\dot{V}O_{2max}$ and resulted in a total explained variation of 74% with a SEE of 358 $mL \cdot min^{-1}$ or 11.7%. The additional explained variance by the fitness index beyond that from BM, age, and gender was 15% ($P = 0.003$). In comparison, when only activity counts were used in the analysis instead of the fitness index, the total explained variation was 71%, and the SEE was 374 $mL \cdot min^{-1}$, or 12.2%. Regression coefficients with standard error, significance levels, and correlations are presented in Table 3. When this prediction equation (equation 2) was used on CV_2, the correlation with measured $\dot{V}O_{2max}$ was 0.85 ($P < 0.0001$), and the SEE was 437 $mL \cdot min^{-1}$, or 14.1%. No significant difference was found between measured and predicted $\dot{V}O_{2max}$ (32 ± 429 $mL \cdot min^{-1}$), and Bland–Altman plotting and linear regression no longer showed a significant relation between the average of predicted and measured $\dot{V}O_{2max}$ and the difference between both (Fig. 2).

$$\dot{V}O_{2max} = 2938 - 38.46*\text{age} + 563*\text{gender} + 27.66*\text{BM} - 4842*\text{HR}\cdot\text{ACM}^{-1} \quad [2]$$

where age is in years, gender = 0 for women and 1 for men, BM is body mass in kilograms, and $HR \cdot ACM^{-1}$ is the fitness index defined as HR over activity counts per minute.

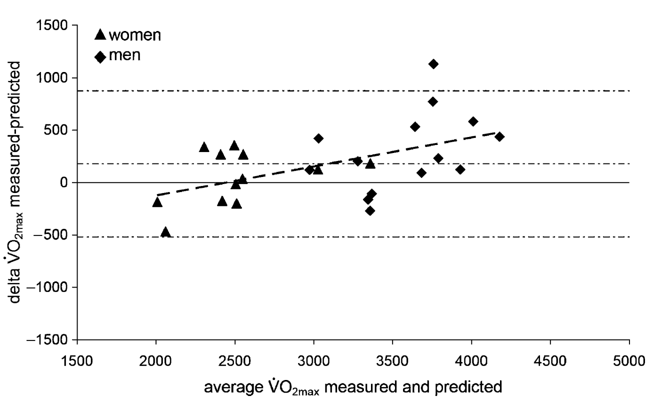

FIGURE 1—Bland–Altman plot for cross-validation group 1 (CV_1): mean $\dot{V}O_{2max}$ (measured and predicted) plotted against the difference (measured vs predicted) in $\dot{V}O_{2max}$. The *striped line* shows the significant positive relation ($P = 0.007$). Mean difference and 95% limits of agreement (mean ± 2SD) are indicated with a *dashed line*.

DISCUSSION

This study tested the validity of our fitness index to predict $\dot{V}O_{2max}$ in a sample of healthy, normal-weight subjects with a wide range of physical activity and fitness. In CV_1, equation 1 resulted in a total explained variation in $\dot{V}O_{2max}$ of 81% with a SEE of 10.7%. In CV_2, equation 2 predicted $\dot{V}O_{2max}$ for 72% with a SEE of 14.1%.

In our previous study (22), an equation was developed to predict $\dot{V}O_{2max}$ from BM, age, gender, and the fitness index $HR \cdot ACM^{-1}$. The number of subjects, however, was too small to create an EXP and a CV group. In this study, we attempted to create a CV group with characteristics comparable to those of the EXP group. However, a significant difference in physical activity existed between groups. Regression analysis showed very good correlation (R = 0.90) between predicted and measured $\dot{V}O_{2max}$, but a systematic difference was seen between predicted and measured $\dot{V}O_{2max}$ of 5.6%. Furthermore, Bland–Altman plotting showed an overprediction of $\dot{V}O_{2max}$ at the lower fitness levels and an underprediction at the higher levels. To test whether this was caused by the difference in physical activity, all subjects were combined, sorted for physical activity, and new EXP and CV groups were created. This technique has been applied by other authors (24). Although equation 2 resulted in a slightly lower correlation (R = 0.85) and larger SEE (14.1%) in the CV group, a systematic bias was not found between predicted and measured $\dot{V}O_{2max}$ as indicated by Bland–Altman plotting.

The practical utility of various protocols to predict $\dot{V}O_{2max}$ can be questioned based on three main considerations: accuracy and validity of the prediction, ease and convenience of the protocol, and generalized application to a broad population. Accuracy and validity of a prediction equation should be evaluated by the correlation coefficient and the SEE in both the EXP and CV groups and by investigating systematic differences between predicted and measured $\dot{V}O_{2max}$. Field tests requiring maximal exertion resulted in good to very good correlations (4,14). Cooper (4)

TABLE 3. Multiple regression analysis with $\dot{V}O_{2max}$ as the dependent variable and age, gender, BM, and HR·ACM^{-1} as the independent variables. Data from experimental group 2 (EXP_2).

$\dot{V}O_{2max}$	Coefficients	SE	P	Correlations (R)		
				Zero-Order*	Partial†	Part††
Constant	2938	596	< 0.0001			
Age (yr)	−38.46	13.92	0.01	0.07	−0.50	−0.30
Gender	563	185	0.006	0.67	0.55	0.35
Body mass (kg)	27.66	7.75	0.002	0.54	0.58	0.38
HR·ACM^{-1} (beats per activity count)	−4842	1417	0.003	−0.49	−0.60	−0.39
Model		SEE				
		358	< 0.0001		R = 0.86	

Gender: women = 0, men = 1; HR·ACM^{-1}, heart rate over activity counts per minute; SEE, standard error of estimate (square root of the average squared error of prediction).
* The zero-order correlation is the simple (Pearson) correlation between the dependent and the independent variable.
† The partial correlation is the correlation between the dependent and an independent variable when the linear effects of the other independent variables in the model have been removed from both.
†† The part (semipartial) correlation is the correlation between the dependent and an independent variable when the linear effects of the other independent variables in the model have been removed from the independent variable only.

reported a correlation of 0.90 between the 12-min performance test and measured $\dot{V}O_{2max}$, but did not provide information about the SEE, and no cross-validation was included. Attempts by other authors to validate this field test resulted in correlations ranging from R = 0.13 to 0.90 (11). Various submaximal tests have yielded correlations ranging from R = 0.46 to 0.95 (11). Many of these tests do not present cross-validation results (6,10,19), require sophisticated laboratory equipment (3,6,19), and do not provide a measure of the SEE (5,9,17,20). When cross-validating a prediction equation, the use of SEE in addition to correlation coefficients is preferred, and mean values of measured and predicted should be comparable (16). George et al. found SEE of 6.5 and 7.5% for a submaximal treadmill jogging test (7) and a 1-mile track jog (8), respectively, both in fit, college-aged individuals. Kline et al. (11) reported a SEE of 12.6% in the CV group for a 1-mile track walk. Naughton et al. (20) validated the Canadian (13) and the European (15) versions of the 20-m shuttle run test in school children and found an underestimation of $\dot{V}O_{2max}$ of 7.7% for the European version and an overestimation of 11.4% for the Canadian version. No estimate of the SEE was provided. Weyand et al. (24) developed a fitness index based on foot–ground contact times and HR during treadmill running. The theoretic model of their fitness index is probably the most closely related to our fitness index, although they did not use a field setting. They found a correlation of R = 0.84 between predicted and measured in the CV group, but no SEE was provided. They did find a systematic difference between measured and predicted $\dot{V}O_{2max}$ of 8.3% (24). Our equation 1 resulted in a SEE of 10.7%, but a systematic difference existed between measured and predicted $\dot{V}O_{2max}$, whereas equation 2 resulted in a slightly higher SEE (14.1%), but without systematic bias. In addition, a Bland–Altman plot showed a positive correlation in CV_1 but not in CV_2. The higher SEE in CV_2 was mainly explained by two outliers, one whose $\dot{V}O_{2max}$ was highly underestimated with the prediction equation, and one whose $\dot{V}O_{2max}$ was highly overestimated. Without these outliers, the SEE in CV_2 was 338 mL·min^{-1}, or 10.9%. The overestimation was in a subject using β_2 agonists, but only as aerosols to treat chronic aspecific respiratory affection (CARA), which was unlikely to affect HR. The underestimation was in a subject who was very fit (53.1 mL·kg^{-1}·min^{-1}) and able to generate a very high maximal HR (193 bpm) for his age (41 yr).

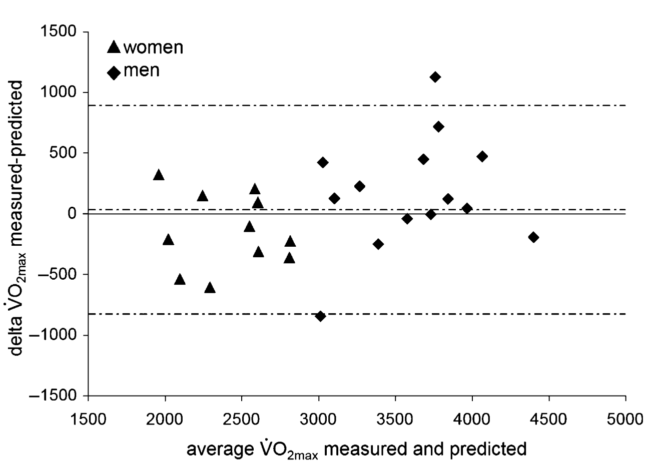

FIGURE 2—Bland–Altman plot for cross-validation group 2 (CV_2): mean $\dot{V}O_{2max}$ (measured and predicted) plotted against the difference (measured vs predicted) in $\dot{V}O_{2max}$. Mean difference and 95% limits of agreement (mean ± 2SD) are indicated with a *dashed line*.

Regarding ease and convenience of the protocol, our fitness measure is very attractive for personal use as well as for research purposes. Because the monitors are worn during activities of daily life, no specific protocol is required. The accelerometer was developed to be unobtrusive in order not to interfere with normal life activity patterns. Given its small size and weight, it was not bothersome to any of the subjects. The HR monitor is sometimes more obtrusive when worn for longer periods, but most subjects enjoyed being able to monitor their own HR during different activities and considered it rather interesting and pleasant. Combining both the accelerometer and the HR monitor into one device would further improve wearing comfort.

Application for a broad population has to be evaluated on different considerations. The sample consisted of healthy, normal-weight and, on average, relatively fit subjects. Validity in study populations different from the one used in this study has yet to be investigated. As seen with EXP_1 and CV_1, differences in daily physical activity can influence the results. Therefore, the prediction equation has to be tested in populations that differ in physical activity and physical fitness from the current one, and population-specific equations might have to be developed. The major advantages, however, are that a specific protocol and maximal exertion are not needed, which makes it useful for subjects with low functional capacity. Therefore, it could be used in a variety of clinical settings, given that the equation has been validated in the population being studied. The total cost of a combined accelerometer/HR monitor should also be considered. In this study, population activity counts alone explained a substantial part of the variation in $\dot{V}O_{2max}$, and thus the addition of HR monitoring to activity monitoring should be evaluated, depending on the research question. Likely, the inclusion of HR monitoring becomes essential when evaluating changes in physical fitness over time.

To our knowledge, this study marks the first attempt to develop a fitness index that does not require a specific protocol, can be used in daily life, is unobtrusive, and is sufficiently accurate. Care should be taken when applying the formula to subjects with a different activity pattern or activity level than was used in the present study. Further research should focus on testing the fitness index in larger and different study populations and on the ability to track changes in fitness over time. Further technical improvement, such as combining both monitors into one device, could improve wearing comfort and might result in even higher accuracy.

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